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# Sediment Transport Patterns in Todos Santos Bay, Baja California, Mexico, Inferred from Grain-Size Trends

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## 1. Introduction

Contaminated sediments do not always remain in the same place in the environment. The mobility of sediments and the contaminants associated to them is a factor that complicates the evaluation of ecological risk, remediation potential and ultimately, the litigation process (e.g., Carriquiry & Sanchez, 1999; Sanchez et al., 2008). A rational decision in this regard must take into consideration the potential stability of contaminated sediments, its sources, transport and final destination (e.g., McLaren & Beveridge, 2006). A technique capable of providing that information in coastal sedimentary environments is the analysis of textural trends of sediments; an empirical method that is based on the relative changes in the grain size distribution of the sediments to determine the net direction of sediment transport (e.g., Sunamura & Horikawa, 1971; McLaren & Bowles, 1985; Gao & Collins, 1992, 1994; LeRoux, 2002; Poizot & Mear, 2008). Because many contaminants become adsorbed to the sedimentary particles, this information can help in evaluating the relationship between contaminant load and its sources, as well as providing an understanding about the behavior and destination of the contaminants in the sediments (e.g., Carriquiry & Sanchez, 1999; Sanchez et al., 2008).

The original theory used to predict the direction of sediment transport based on the relative change in the particle size distribution was given by Sunamura & Horikawa (1971). Later on, McLaren & Bowles (1985) proposed a one-dimensional approach in which changes in the grain size distribution along a sequence of individual samples that were statistically analyzed by a Z-test could be used to determine the preferred transport direction. Gao & Collins (1991, 1992) and Gao (1996) proposed a two-dimensional model to determine the trend on the basis of vector analysis. A different approach based on analytic geometry and vector analysis to determine the direction of sediment transport was produced by LeRoux (1994) and LeRoux et al. (2002). A summary of all these techniques is provided by Poizot et al. (2008).

In all the sediment transport models based on trend analysis of clastic material, there are considerations that limit the inferences made on the net direction of sediment transport. The

most important limitation is the inability to validate the obtained transport trends with hydrodynamic observations in the field. In this chapter we will use the model proposed by LeRoux et al. (2002) to identify the dominant paths of sediment transport based on sediment characteristics and dynamics. The sediment transport model obtained with the LeRoux model is compared with sediment transport inferences made by Sanchez et al. (2009). Subsequently, the model is validated with hydrodynamic observations in the bay. Later, we assess the likely extent of dispersion of specific sources of pollution in the Todos Santos Bay, off Ensenada, Baja California, Mexico. With this goal we will use additional studies of the distribution of organic and inorganic pollutants carried out in this bay.

### 1.1 Study area and method

Todos Santos Bay (TSB) is located on the west coast of the peninsula of Baja California, Mexico, between 31°41' and 31°56'N and 116°34' and 116°51'W (Fig. 1). The natural boundaries are Punta San Miguel to the north, Punta Banda to the South and the Todos Santos Islands (TSI) in the center, which define two entrances to the bay and permit a constant circulation of ocean water. The coastline of the bay consists of a rocky shore that encompasses Punta San Miguel, Punta El Sauzal, Punta Morro and Punta Ensenada, with pocket beaches between them. Punta El Sauzal and Punta Ensenada form natural breakwaters that protect the ports of El Sauzal and Ensenada, respectively. A sandy beach, 14 km long, starts at the South of the port of Ensenada and ends at the base of Punta Banda. This beach is interrupted by an inlet that defines the entrance to a coastal lagoon known as the Punta Banda Estuary. The rocky shore of Punta Banda is very irregular, with almost vertical cliffs and small beaches with little sand between them. The bathymetric configuration of the bay is irregular. The most notable features are: (1) the shoal of San Miguel, with a minimum depth of 5.5 m, located between Punta San Miguel and the Todos Santos Islands; (2) a submarine depression between Punta Banda and the islands, known as the Todos Santos submarine canyon, with depths of 550 m.

In the Todos Santos Bay several studies have been conducted on littoral transport. In the north of the bay, sediment transport is towards the SE and to the central part of the bay, the sediment transport is predominantly in the direction NE-N with a W-component near the mouth of the Punta Banda coastal lagoon (Pérez-Higuera & Chee-Barragán, 1984). The sediment dispersion pattern presents several transport directions within the Todos Santos Bay (Sanchez et al., 2009). In the North of the bay the transport direction is SE (following the isobath contour of 20 m) and towards the NE (near the Todos Santos Island). In the South of the bay, transport direction is NE. In the central region of the bay there is a westerly transport direction. In the Todos Santos canyon a NE trajectory was determined. In the external region of the bay, in front of the Todos Santos Islands and the Peninsula of Punta Banda, the inferred transport is to the W. The central zone of the bay seems to be a convergence zone which in practical terms becomes a depocenter, a site of sediment accumulation.

Sediment samples were collected using a van-Veen grab during cruises OGEO-0893 of the Mexican Navy that consisted of a sampling grid of 51 stations (Fig. 1). The first 5 cm of surface sediments of each grab sample were collected. Later in the lab the samples were treated to remove organic matter and salts (Mook & Hoskin, 1982). The granulometric analysis was performed by the technique of Ingram (1971) for the sand fraction and Galehouse (1971) for the fine fraction (silt and clay). Sediment textural parameters (mean grain size, sorting and asymmetry) were calculated by the method proposed by McManus (1988).

## 1.2 Sediment transport model

Sediment transport models have allowed coastal oceanographers to infer the residual sediment transport based on spatial trends of sediment (e.g., McLaren & Bowles, 1985; Gao & Collins, 1992; LeRoux, 1994; Poizot & Méar, 2008). In this study, the model proposed by LeRoux (1994), based on principles of analytic geometry and vector analysis of textural data, was used. With this method, the vector's magnitude and direction (of transport) were obtained by comparison of the textural characteristics of five neighboring sampling stations (one central and four satellites). General considerations of the model are: (1) textural trends result from the hydrodynamic conditions of the environment, (2) it is applicable in coastal zone and shelf where sediment transport is unidirectional, (3) the gradient between textural parameters is constant in the area where we compared the five sampling stations, (4) textural parameters in the model have the same weight and importance, and (5) the distance between the five stations (inter- seasonal) is not critical, especially if there is a clear textural gradient between stations.

## 2. Results and discussion

### 2.1 Grain-size trends

Sediment characteristics in the bay have been extensively studied since the 1950s (e.g., Walton 1955; Emery et al. 1957) who emphasized the importance of topographic details and hydrography in controlling grain size. Grain-size decreases from the coastal regions (0.0  $\phi$ ) into the canyon (7.0  $\phi$ ). Also, there was a slight decrease in this parameter in the deepest region of the study area (>8.0  $\phi$ , Fig. 2). The spatial distribution of grain-size denotes the monotonous tendency to decrease (larger phi values) with the depth of seabed. The silt fraction is dominant in two areas: (1) medium silt in the deepest region in the inner-bay (head of the canyon) and (2) fine silt to clay outside the bay (continental slope). The shallow inner-shelf is characterized by fine to very fine sand with some small areas consisting of medium to coarse sand (Fig. 2). The grain-size distribution is very similar to that reported by Smith et al. (2008), where the grain-size is dominated by silt. The spatial trend of grain size indicates a zone of deposition of fine material in the central area of the bay (a depocenter), consistent with the convergent surface current system, longshore transport and sediment transport in the bay (Sanchez et al., 2009). Although grain size was used as a good indicator of sedimentary dynamics, in most cases is not fully robust due to other sediment sources. Hence, it is necessary consider additional parameters such as sorting and asymmetry of the same sample (e.g., McLaren and Bowles, 1985). The sorting parameter was considered by Sunamura and Horikawa (1971) to be a good estimate of the dispersion of sediments in marine environments, where the contribution of other sources of sedimentary material was insignificant (e.g., from cliffs, streams, etc). Sunamura and Horikawa (1971) indicated that sediments will move in the direction where the average grain size decreases and the sorting of the sedimentary material increases. The surface sediments were well-sorted in shallow stations, where the average grain-size is larger with respect to the deeper stations. In the deepest part of the bay, the sediments were poorly-sorted and grain-size decreases toward the region of the canyon (Fig. 3). Negative skewness values (sediments with an "extra load" of coarse grains) are found in shallow areas, increasing in the central part of the bay; the trend reverses to negative values towards the canyon (Fig. 4).

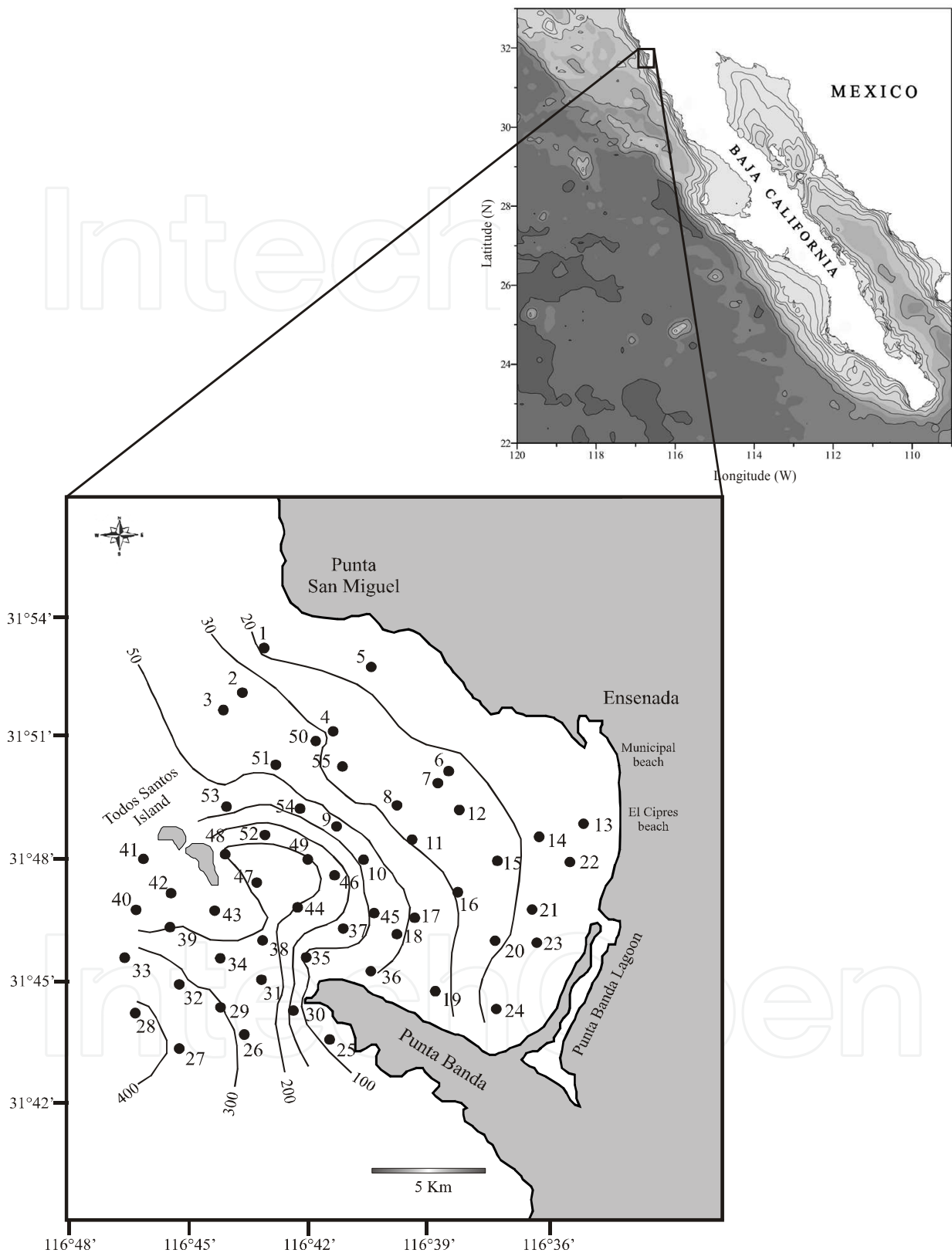


Fig. 1. Stations of collect of surface sediments in the Todos Santos Bay, Baja California, Mexico. The continuous lines correspond to isolines of bathymetry (20, 30, 50, 100, 150, 200, 300 and 400 m depth).



In their model, McLaren and Bowles (1985) also included the parameter of asymmetry in order to yield a more robust estimate of sediment transport paths. Thus, while the combination of sediment textural parameters define the existence of several sediment transport paths, the sorting improves or strengthens the interpretation of sediment transport direction (e.g., McLaren and Bowles, 1985; Gao and Collins, 1992; LeRoux, 1994; Carriquiry and Sánchez, 1999; Carriquiry et al., 2001; Poizot and Méar, 2008; Sánchez et al., 2008, 2009, 2010).

Sanchez et al. (2008, 2010) applied a principal components analysis (PCA) to the sediment textural parameters in both studies, the spatial trends of grain size and sorting explained at least 75% of the variance and 20% of the variance was explained for asymmetry. The remaining 5% of the variance can be related to other factors such as sampling depth, the distance between stations, among others, affecting the distribution of sediment textural parameters (e.g., Poizot et al., 2008). In the case of the surface sediments of the bay, the grain size and sorting explain 50% of the variance and asymmetry, 34% of the variance. These contrast with the results obtained for grain size and asymmetry that describe 95% of the variability of spatial trends of textural parameters in the sediments in the Yellow Sea, China (Cheng et al., 2004). The difficulty of establishing a spatial trend in very fine grained estuarine sediments occurs because flocculation can result in the preferential deposition of fine particles in the environment. Thus, the difference of each factor in the PCA, for each comparison site can be result from processes of flocculation derived from sedimentary material, which allowed the settlement of poorly sorted material in the Yellow Sea, China and Upper Gulf of California, Mexico and Todos Santos Bay, Baja California, Mexico. While, the low discharge of streams in the Bahia Magdalena, Baja California and Hondo River in the Bahia of Chetumal, Quintana Roo, Mexico, caused the well-sorted sediment deposition.

## 2.2 Sediment transport models

The spatial trend analysis method used to infer the net transport of sediments has been widely applied in various settings of marine and continental environments. In these studies, the net transport and dispersion of sedimentary material have been effectively validated by comparing the resulting transport vectors (defined from the transport models) with the observed ocean currents (*in situ*) (e.g., McLaren and Bowles, 1985; Gao and Collins, 1992; LeRoux, 1994; Carriquiry and Sánchez, 1999; Carriquiry et al., 2001; Poizot et al., 2008; Sánchez et al., 2008, 2009, 2010). Consequently, these results have provided confidence in these models, becoming an excellent tool for inferring the transport direction of sediment particles in places where ocean current studies are limited.

The model of Sunamura and Horikawa (1971) is the most basic and unidirectional, where was identifying sediment source and the final destination of the particles, based on comparison of grain-size and sorting. The asymmetry is not used as an additional comparison criterion; making is less sensitive to identify an exchange of material and sediment transport. In fact, the principal component analysis indicated that the asymmetry explain 34% of the variance of the spatial trend. Therefore, the asymmetry is a criterion that must be considered to define transport paths more robust (e.g., Cheng et al., 2004; Sanchez et al., 2008, 2010).

The one-dimensional method McLaren-Bowles was developed for studies of longitudinal environmental systems, such as rivers, beaches and sand bars (Mc Laren and Bowles, 1985).

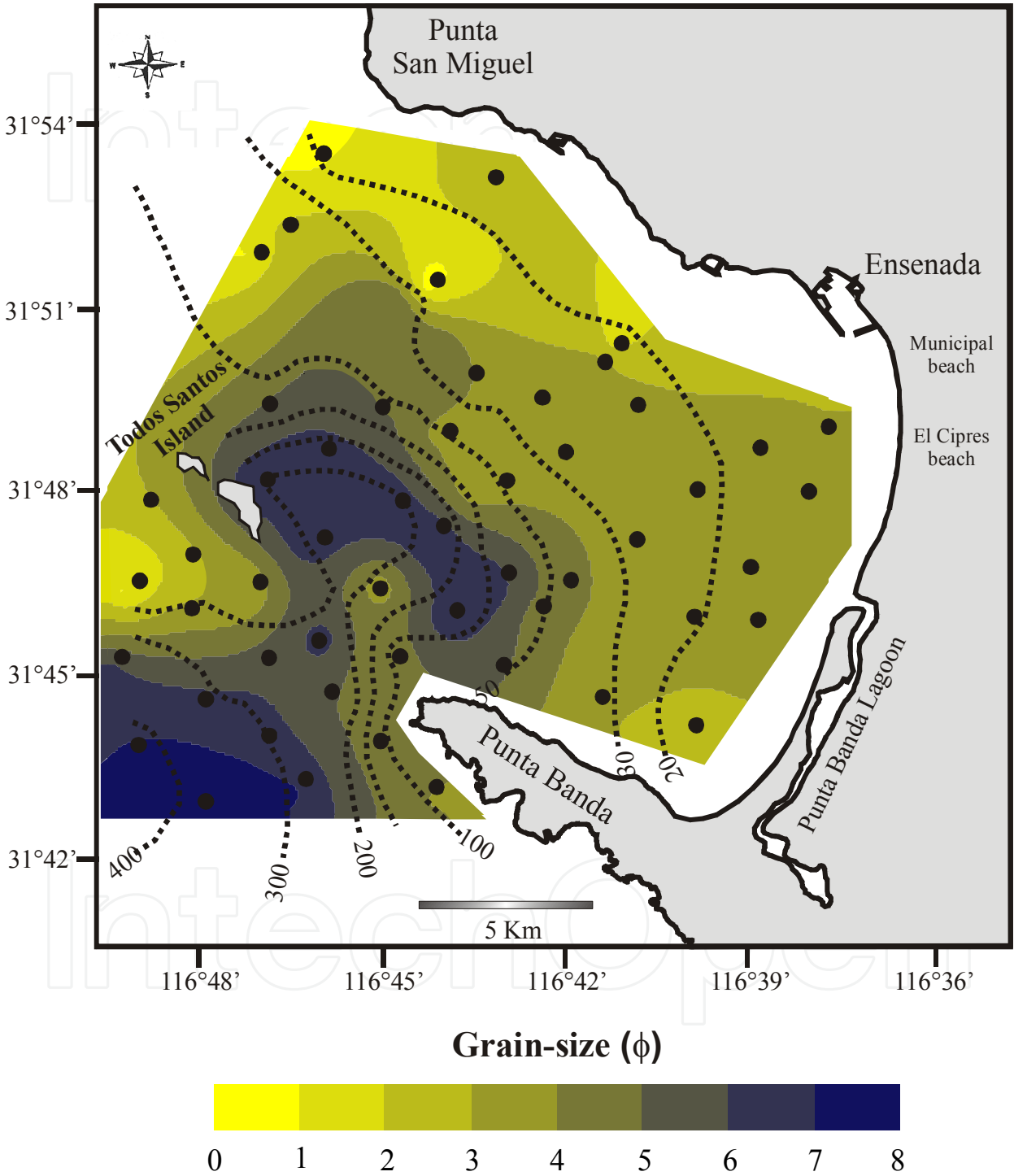


Fig. 2. Spatial distribution of the grain-size (phi units) of sediments in the Todos Santos Bay, Baja California, Mexico. The segmented lines denote the bathymetry (m) of the bay.

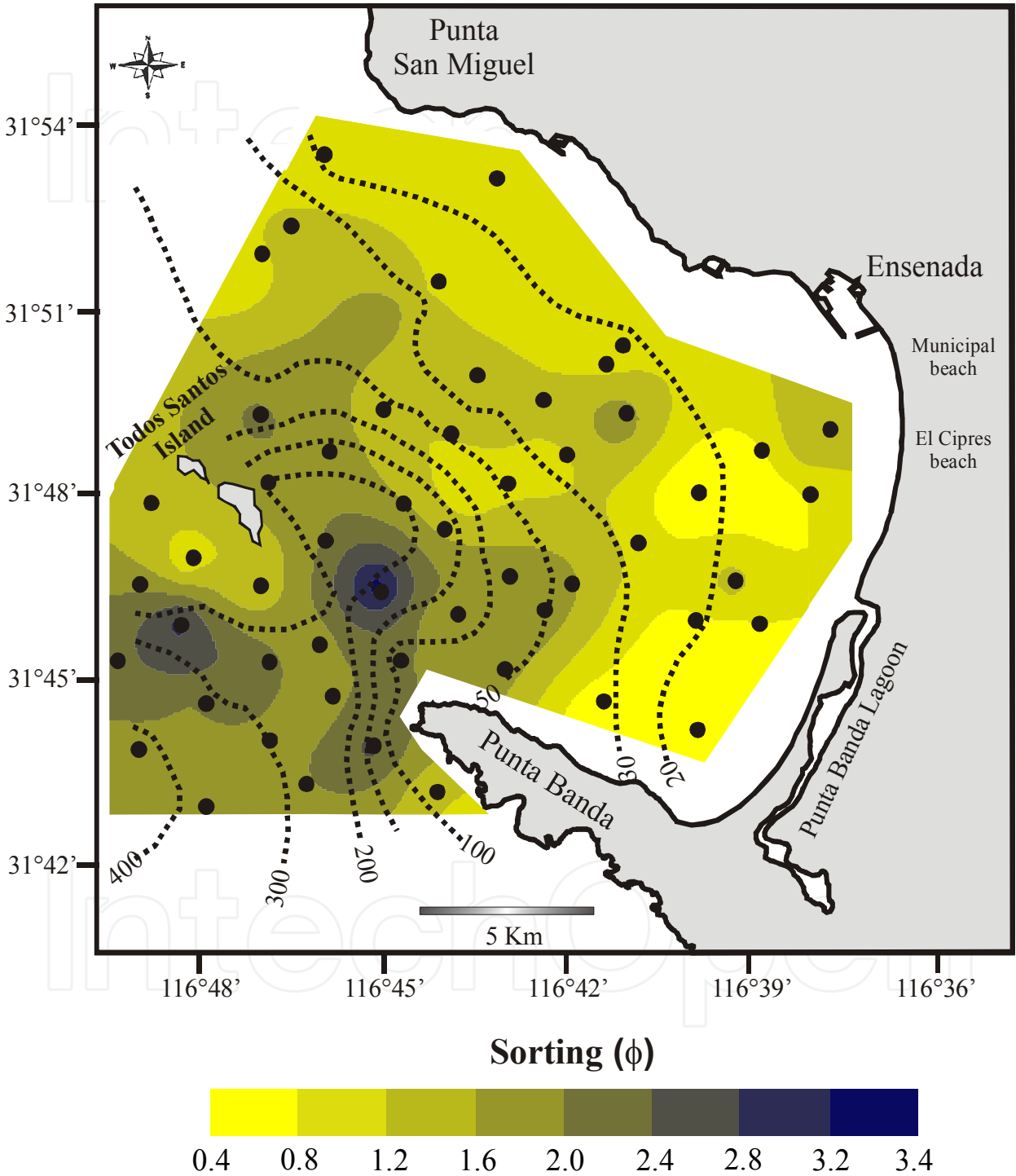


Fig. 3. Spatial distribution of the sorting (phi units) of sediments in the Todos Santos Bay, Baja California, Mexico. The segmented lines denote the bathymetry (m) of the bay.



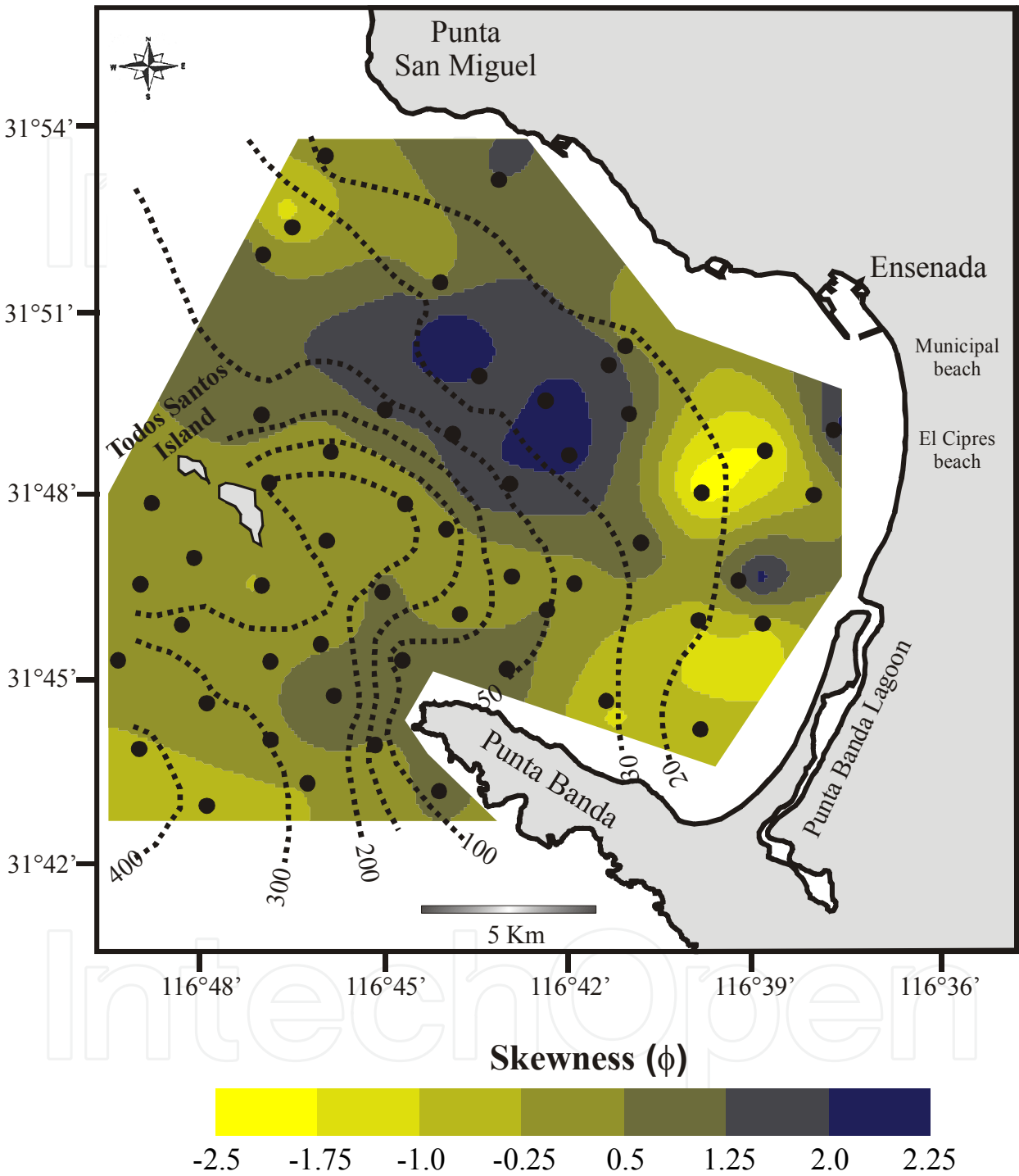


Fig. 4. Spatial distribution of the skewness (phi units) of sediments in the Todos Santos Bay, Baja California, Mexico. The segmented lines denote the bathymetry (m) of the bay.

This model analyzes the grain-size evolution along sampling paths (samples in a linear sequence). To study a more complex area and obtain transport paths in two dimensions requires a 9x9 grid containing 81 samples (Mc Laren and Little, 1987). Masselink (1992) concluded that the unidimensional model is limited and Lanckneus et al. (1992) showed that

when sediments become finer and better sorted, the corresponding skewness becomes more positive, which is in contradiction with the sediment transfer function of McLaren and Bowles (1985). The McLaren and Bowles model was applied to 17 locations and were valid in 7 of them; the other cases were partially correct or unacceptable (Poizot et al., 2008). In fact, the results of this study seem to confirm that the one-dimensional model has limitations in complex environments such as the TSB (Sanchez et al., 2009).

Gao and Collins (1992) developed a bidimensional model where vectors are determined by comparing the sedimentary textural parameters in a sampling grid. The distance used for "neighboring" stations is determined on the basis of a characteristic distance that represents the spatial scale of sampling. However, the resultant vector can be affected by the magnitude of such characteristic distance; in other words, if the distance is too great, it may yield a change in the direction of the vectors with one direction that is not representative of sediment transport. For the Todos Santos Bay we applied various distances and sampling densities ( $\pm 50\%$ ) and the observed effect on the model output did not show any significant differences in the model outputs.

In the Le Roux model, sampling sites are rarely located on a regular grid pattern. When the sampling scheme is not regular and there are many discontinuities, edge effects are very noticeable and can become dominant in some parts of the studied areas (Poizot et al., 2006). If an irregular sampling scheme is used, a regular grid can be created by interpolation of the dataset. This procedure was used by Ríos et al. (2003), Friend et al. (2006), Lucio et al. (2006) and Poizot et al. (2006). However, Le Roux and Rojas (2007) argue that interpolation alters the original data distribution and diminishes the reliability of the method. Despite the use of a regular grid, edge effects can persist within the intended mapping area. In the present case, edge effects can affect both the averaging procedure and the definition of the trend vectors. For a site at the centre of a grid, trend vectors are calculated with more sites, lying within a defined characteristic distance, than sites on the edges of the grid (Gao and Collins, 1994a,b). This effect is increased at the corners of the grid. Such effects are likely to introduce some distortions, so sediment trend vectors along the edges of the sampling grid should be applied with caution in the final interpretation.

In this study, the edge effect was estimated by increasing the number of stations around the sampling grid located within a spatial distance-unit (minimum distance between stations). In the model of Sunamura and Horikawa (1971) the edge effect was observed in the residuals of the marginal stations that indicated a transport direction that differed by  $45^\circ$  from expected. Subsequent calibration of the model by using a one-unit distance, we observed an improvement in the residuals showing only a deviation of 15 degrees from expected. In the model of McLaren and Bowles (1985) no edge-effect problems arise due to its unidirectional character of the model (stations along a linear sequence of stations). The models of Gao and Collins (1992) and LeRoux (1994a, b) despite having an edge effect, there appears to be insignificant in our study since the delineated net transport paths match the expected transport direction, and the differences observed with the model before and after applying the calibration series is very small ( $<5^\circ$ ) with respect to the calibration standards. The observed edge effect declined when using a space-distance no greater than the spatial unit of the calibration series, and also yields a net transport direction closer to the expected path.

### 2.3 Dispersion pattern

The dispersion pattern for the TSB is consistent with the general pattern of water circulation (Argote-Espinoza et al., 1975, Alvarez-Sánchez et al., 1988) and the observed longshore currents (Perez-Higuera and Chee -Barragán, 1984) proposed for the site. In shallow areas, the sedimentary material can be transferred and reworked by the longshore current to later be driven out of the surf zone following a transport path perpendicular to the coast (eg, Cruz-Colin, 1994). These observations allow us to identify the existence of materials exchange between those stations near the beach. Carriquiry (1985) found a decrease in the amount of heavy minerals from the north entrance of the bay towards the central bay, coincident with transport direction proposed in this work, assuming that the heavy mineral concentrations are higher in the source area of the material and decreasing in the direction of transport (e.g., Carriquiry and Sánchez, 1999). The transport observed in the central region of the bay to SE direction (Fig. 5) may indicate the transfer of materials to the bay's interior (Cruz-Colin, 1994) resulting from the convergence of longshore currents in the area (Pérez-Higuera and Chee-Barragán, 1984).

In the northern region of the bay near the Punta San Miguel there is a transport to the NE. The component one (daytime) and two (semidiurnal) of the tidal-ellipse indicate the predominant orientation of the tidal wave motion, which coincides with the sediment transport direction obtained in this study (Figure 5).

Hydrodynamic effects of tidal processes, such as residual currents, may be the cause of materials exchange and transport in this area. Towards the center of the bay, the sediment transport direction converges predominantly in a direction towards the southeast (Fig. 5). This same pattern of sediment transport was observed using the model Sunamura and Horikawa (1971), and Gao and Collins (1992); reported by Sanchez et al. (2009). The dispersion of sediments to the central region of the bay coincides with the predominant orientation of the tidal components (components one and two) which converge towards the central part of the bay. In fact, by using the Regional Ocean Modeling System Model (ROMSM), Mateos et al. (2009) observed the persistence of a convergent circulation with a southeast direction, in front of the port of Ensenada, with a clear path towards the Todos Santos submarine canyon (Fig. 5). In the deeper region of the study area, the direction of the sediment transport occurs in two patterns. In the area of the Punta Banda peninsula, the sediment is transported out of the bay with a westward component whereas in the northern entrance of the bay, nearby the Todos Santos islands, the sediment is transported into the bay with a direction east-northeast (Fig. 5). Cruz-Colin (1997) calculated the velocity of the approaching tidal waves, at different depths within the bay, finding an average velocity of 0.20 m s<sup>-1</sup>. This author also observed that the speed directly increased as a function of depth, and calculated a velocity of 0.32 m s<sup>-1</sup> at a depth of 476 m. These observations indicate that hydrodynamics at this depth is capable of resuspending (Shepard and Keller, 1978) and transporting (Komar, 1977) sediments of grain size between 3 to 5  $\phi$ . These calculations have been corroborated by a series of current measurements which reach 0.30 m s<sup>-1</sup> at a depth of 308 m in the canyon (Garcia et al., 1994). In addition to identifying a net direction of flow to the northwest, which agrees with that obtained in this work, Mateos et al. (2009) suggests two modes of circulation for a deep section between Punta Banda and Todos Santos Islands by implementing the ROMSM model (their Figure 2). This deep section can be considered as an exterior and interior threshold system. The external system is characterized by an intense circulation flow out of the bay in the upper 30 m and

diminishes down to 1 cm s<sup>-1</sup> at 250 m depth, covering 2 / 3 of the cross depth-section. The flow into the bay adjacent to the islands occurs below 50 m depth with a speed of 1 cm s<sup>-1</sup> and increases up to 3 cm s<sup>-1</sup> to 150 m deep. In fact, Gavidia-Medina (1988) calculated the tidal residual currents for TSB, identifying an anticyclonic eddy in the canyon area, finding greater magnitudes inward than outwards. Therefore, residual tidal currents can become important enough in the net transport of sedimentary material along the canyon towards the interior of the bay.

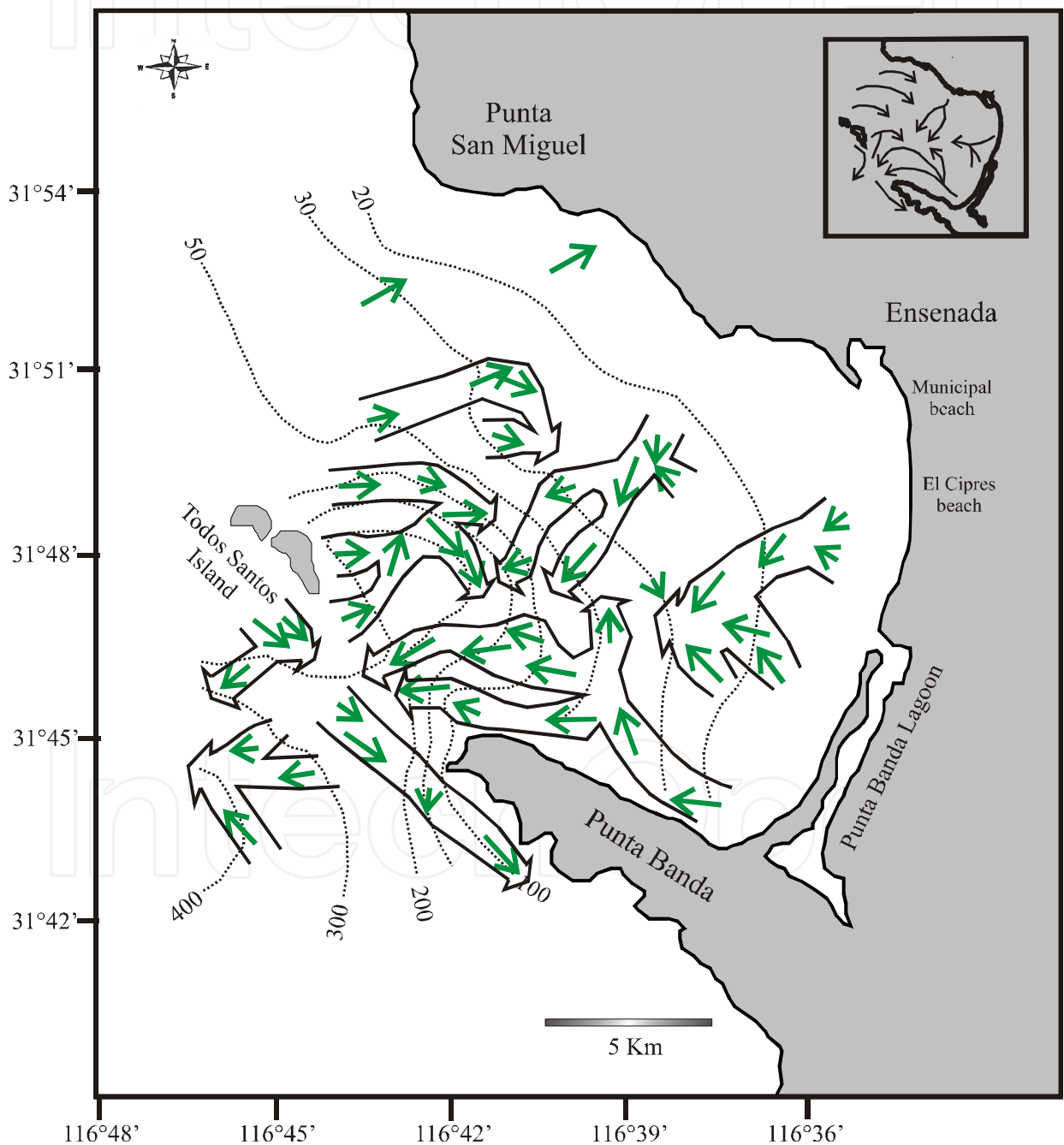


Fig. 5. Dispersion pattern of sediments in the Todos Santos Bay, Baja California, Mexico inferred from transport vectors. The segmented lines denote the bathymetry (m) of the bay.

Submarine canyons can actively function as a structural traps of sedimentary material, especially when there is a net flow downward through the canyon; those with coarse materials (coarse sands) in the deep regions are considered as dead or inactive (Shepard and Marshall, 1973). In the latter case, current speeds of  $0.44 \text{ m s}^{-1}$  have been observed, capable of transporting sediments upslope (Shepard and Marshall, 1973, Shepard and Keller, 1978). The possibility of sediment transport upslope the submarine canyons may seem intuitively difficult, however, depending on the hydrodynamics prevailing at the canyons' mouth it is possible to promote a net upcanyon transport of sedimentary material. The existence of flows with high enough speed ( $0.30 \text{ m s}^{-1}$ ), capable of resuspending and transporting sediment (of 3-4 $\phi$  grain size) suggests that somehow, different processes such as the California Countercurrent, internal waves propagating towards the coast or residual tidal currents, independently or in combination, can promote the movement of particles in the direction proposed by this study (i.e., upslope the canyon).

The dispersal pattern of sediments proposed for TSB seems to promote the development of a site of convergence in the central region (e.g., a depocenter), rendering the particles to environmental stagnation (eg, pollutants) in this convergence zone or depocenter. This zone not only collects the sediments that naturally converge here, but also retains the exogenous materials generated from the dredging of the port that are dumped in the vicinity of the stations 9, 46, 47, 49, 51, 52 and 54. In a study on metals distribution in sediments within Bahía de Todos Santos, Romero-Vargas-Marquez (1995) reported the highest concentrations of several metals, including Cd, Cu, Zn, and Ni in the dredge discharge area and inside the port. Furthermore, in a study in which sediment samples were collected along the coast of Baja California from the México-USA border to Todos Santos Bay, Sandoval-Salazar (1999) reported that the sediments most enriched in metals (e.g., Cd, Ag, Cu, Pb, and Zn) were found around the Todos Santos Islands. Analysis of the 16 polycyclic aromatic hydrocarbons (PAHs) listed as priority pollutants by EPA, was carried out on surface sediments at Bahía de Todos Santos, Baja California, Mexico. The PAHs composition of car exhaust, grass and shrubs combustion, asphalt and tire dust, were all compared to the relative abundance of PAHs signature found on marine sediments of the bay. These studies found that surface distribution of PAHs in TSB coincided with the reported water circulation in the bay. The lower concentrations were found in stations near the coast. Since this zone corresponds to the sedimentary environment with the highest energy relative to the rest of sampling sites, it is unlikely that particles accumulated in this part of the bay, and hence unlikely to find hydrocarbons associated with this material. The higher concentrations found around the Todos Santos island clearly suggest that this is a natural deposit area for particulate material such as this (rich in associated contaminants). This area is probably a good place for preservation of PAH's and other synthetic organic molecules, specially those that are difficult to decompose by bacterial attack (Villegas-Jimenez et al., 1997).

### 3. Conclusion

The principal component analysis applied to textural parameters indicate that the sediment grain size and sorting significantly contribute to the spatial trends that define the dispersion pattern of sediments in coastal environments. By considering all these parameters in the analysis has the advantage of generating a more robust definition of net sediment transport. The model of sediment transport applied to textural trends of sediments in the Todos Santos Bay indicates that the two-dimensional model of LeRoux defines sediment transport paths



that agree with the hydrodynamic characteristics of the bay (surface, subsurface/bottom currents). This model is also consistent with the one-dimensional model of Sunamura-Horikawa and with the bi-dimensional model of Gao-Collins. All these models of sediment transport in BTS broadly define a transport from the coastal areas and from the Todos Santos Islands converging into the center of the bay, indicating the existence of a depocenter that naturally accumulates sediments. This depocenter zone is now being used to dump contaminants dredged from the port of Ensenada, creating an environmental health hazard that could be avoided if the dumping site were located outside the bay at greater depths.

#### 4. Acknowledgment

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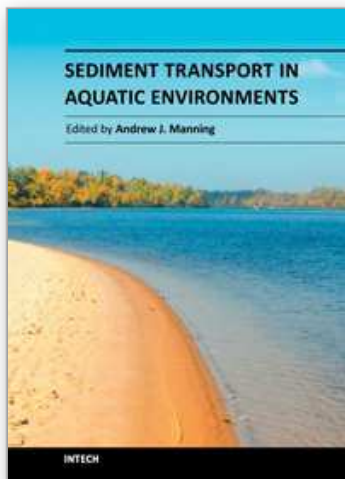


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## **Sediment Transport in Aquatic Environments**

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Sediment Transport in Aquatic Environments is a book which covers a wide range of topics. The effective management of many aquatic environments, requires a detailed understanding of sediment dynamics. This has both environmental and economic implications, especially where there is any anthropogenic involvement. Numerical models are often the tool used for predicting the transport and fate of sediment movement in these situations, as they can estimate the various spatial and temporal fluxes. However, the physical sedimentary processes can vary quite considerably depending upon whether the local sediments are fully cohesive, non-cohesive, or a mixture of both types. For this reason for more than half a century, scientists, engineers, hydrologists and mathematicians have all been continuing to conduct research into the many aspects which influence sediment transport. These issues range from processes such as erosion and deposition to how sediment process observations can be applied in sediment transport modeling frameworks. This book reports the findings from recent research in applied sediment transport which has been conducted in a wide range of aquatic environments. The research was carried out by researchers who specialize in the transport of sediments and related issues. I highly recommend this textbook to both scientists and engineers who deal with sediment transport issues.

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